New development of rapid-solidified Fe-Ga sensor/actuator alloy

T. Okazaki*, Y. Furuya, C. Saito, Hirosaki Univ., Hirosaki, 036-8561, Japan; T. Watanabe, Touhoku Univ., Sendai, 980-8579, Japan; M. Wuttig, Univ. of Maryland, College Park, 20742-2115, USA.

Abstract

Rapid-solidification method was applied to make Fe-15at%Ga and Fe-17at%Ga ribbons of 100 μm thickness. These ribbons have large magnetostriction of 270 ppm, where the coercive force exhibits a maximum value. The phenomenon is related to special metallic texture, that is, the ribbon has strongly [001]-oriented textured fine columnar microstructure with grain size of 2~5 μm. The ribbon has little-hysteresis loop of magnetostriction and a good ductility (i.e., full bending is possible). Rapid-solidified Fe-Ga alloy has a promising possibility as a new magnetic-induced sensor/actuator material.

1. Introduction

Inexpensive magnetostrictive materials which exhibit reversible strains for applied magnetic field are demanded for sensor /actuators. Terfenol-D [1] and ferromagnetic shape memory alloys [2-5] have large magnetostriction. Recently, Clark et al. demonstrated that a large magnetostriction of 300 ppm (10^{-6}) in Fe-17at%Ga single crystal [6] and of 271 ppm in polycrystalline Fe-27.5at%Ga rods [7] occur at room temperature. However, many of those materials are brittle polycrystals or expensive single crystals. Furthermore, the shape of rod type has a limit in applicability owing to the loss caused by eddy current.

In a previous study [8,9], we showed that polycrystalline Fe-29.6at%Pd ribbons prepared by rapid-solidification melt-spinning method with simple, one processing technique have fine columnar microstructure with strong [100]-oriented texture and exhibit giant magnetostriction of 1000-1800 ppm with good shape memory effect.

In this study, we applied the melt-spinning method to $Fe_{1-x}Ga_x$ (x=0.137, 0.151, 0.173) alloy with bcc phase in order to get inexpensive, ductile and strong polycrystalline magnetostrictive materials. We analyze the texture of ribbon by using XRD and SEM-EBSP/OIM. The as-spun ribbon has a strong [001]-oriented texture which induces magnetic anisotropy and large magnetostriction.

2. Experiment method

Ingots of three kinds of composition, Fe-13.7at%Ga, Fe-15.1at%Ga and Fe-17.3at%Ga were prepared from electrolytic iron (4N) and gallium (5N) by using arc-melting method in Ar atmosphere. They were annealed at 1173 K for 24 hours in order to make the alloys homogeneous. The ribbon samples of about 100μm in thickness were produced from these ingots by using original designed melt-spinning apparatus with iron single roll in Ar atmosphere, as schematically shown in Fig.1. The composition of these ribbons was checked by using Electro Probe Micro Analyzer. The bulk sample (5x4x1 mm^3) was cut off from each ingot.

The surface and the cross section of the ribbon sample were observed with laser microscope. The photograph of the cross section, which is also shown in Fig.1 exhibits fine columnar microstructures of about 5 μm parallel to the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **00 JUN 2003**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **New development of rapid-solidified Fe-Ga sensor/actuator alloy**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Hirosaki Univ., Hirosaki, 036-8561, Japan; Touhoku Univ., Sendai, 980-8579, Japan; Univ. of Maryland, College Park, 20742-2115, USA.**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001697, ARO-44924.1-EG-CF, International Conference on Intelligent Materials (5th) (Smart Systems & Nanotechnology)., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

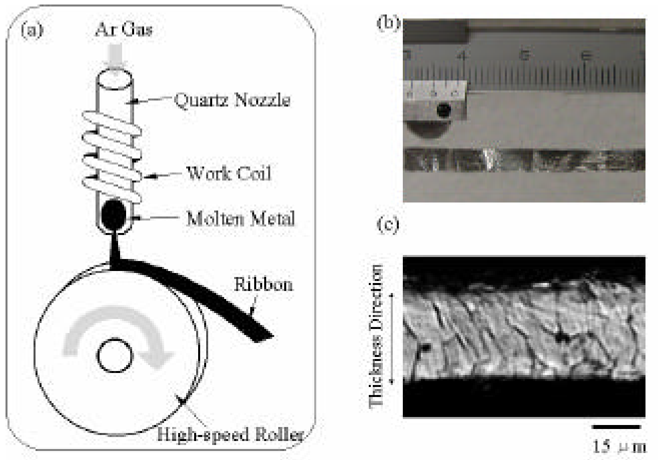

Fig.1 (a) Schematic diagram of melt-spinning single roll method, (b) ribbon and
(c) laser microscope photograph on cross-section of ribbon.

thickness direction, which coincides with the direction of crystal growth. The structure and inverse pole figure for ribbon were analyzed by using XRD and Backscattering Pattern/Orientation Imaging Microscopy (SEM-EBSP/OIM). Magnetization M v.s. applied magnetic field H loop of ribbon was measured with VSM in various angles (see Fig.5).

Magnetostriction was measured by the strain gauge method. Since the ribbon sample is thin foil, the ribbon was weighted on the bottom and then the ribbon under loading stress of 10 MPa was hanged in the magnetic field center as shown in Fig.5. Moreover, magnetostriction was determined by averaging values obtained from strain gauge on both surfaces.

3. Results and Discussion

3.1 Structure and Texture of Ribbon

Strength for the three ribbons was investigated by bend-ductility test. The ribbons didn't break even for bending angle of 180º.

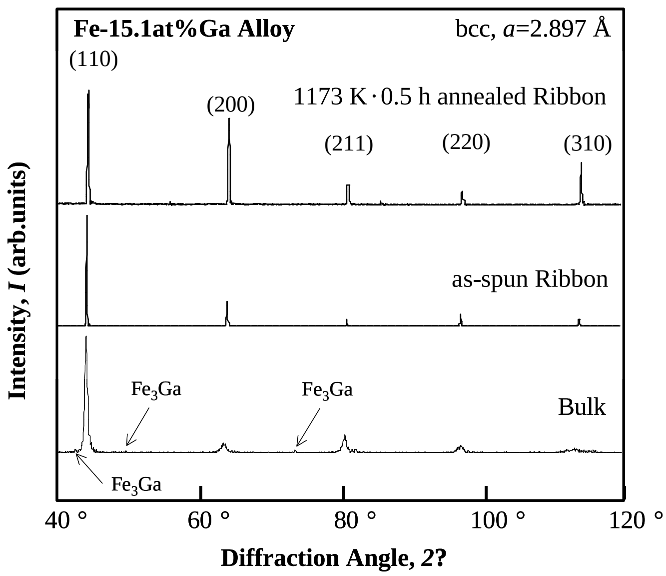

Fig.2 X-ray diffraction pattern of Fe-15.1at%Ga alloy.

Figure 2 shows XRD patterns obtained for the bulk and the ribbon samples of Fe-15.1at%Ga alloy, in which the ribbons are as-spun or annealed for 0.5 h at 1173 K. XRD(110), (200), (211) , (220) and (310) peaks exhibit that the alloy consist of bcc structure with lattice constant a of 2.897 Å. However, for bulk sample, two weak peaks of Fe_3Ga with fcc phase whose lattice constant a=3.683 Å also appear at 2?=42.7º and 77.5º. XRD pattern obtained from

Fe-13.7at%Ga and Fe-17.3at%Ga ribbons also shows the bcc structure of a=2.896 and 2.901 Å, respectively. The lattice constant slightly increases with Ga content.

As shown in Fig.2, the (200) peak intensity for annealed ribbon at 2?=64.4º increases as compared to other peaks. The result suggests that the ribbon has [100]-oriented texture. In order to investigate the texture of ribbons in detail, the inverse pole figure and the grain size for Fe-15.1at%Ga were analyzed by SEM-EBSP/OIM system.

The grain structure maps for ribbons annealed for 0 h and 6 h at 1173 K were obtained by OIM and these maps show that these polycrystals consist of grains of the average size of 4 and 10 µm, respectively. The inverse pole figures for three ribbons annealed for 0 h, 0.5 h and 6 h at 1173 K are shown in Fig.3, where RD and TD mean directions parallel and perpendicular to the rolling direction of ribbon (see Fig.5). The ribbons short-annealed for (a) 0 h and (b) 0.5 h clearly show sharp texture. It is seen that the [001] axis of many grain in Fig 3(a) and (b) orients in the range of 0º to 40º and 10º to 40º from pole in inverse pole figure, that is these ribbons tend to have a strong [001]-oriented texture and the tendency is increased by short annealing. On the other hand, the grain of ribbon long-annealed (c) for 6 h has randomly oriented texture.

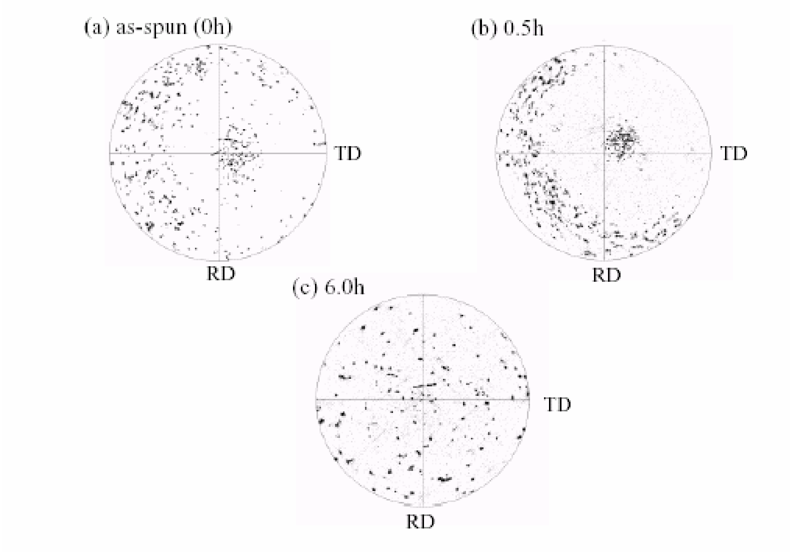

Fig.3 Pole figure of Fe-15.1at.%Ga ribbons annealed for (a) 0 h (as-spun), (b) 0.5 h, (c) 6.0 h at 1173 K.

3.2 Heat-treatment Effects on Magnetostriction

Figure 4 shows (a) the *M-H* loops of as-spun Fe-17.3at%Ga ribbon and (b) the coercive force *H*c obtained from the *M-H* loops as a function of ?, where ? is rotation angle of sample (as for the definition of ?, see Fig.5). *H* is parallel (TD) and normal to sample plane when ?=0º and 90º, respectively. Magnetization for ?=0º is quickly saturated in a weak magnetic field less than 2 kOe and its saturation magnetization is 184 emu/g which is 83.6 % value of pure iron. On the other hand, for ?=80º, because of occurrence of strong demagnetizing field, there is no sign that magnetization is saturated even after the field of 10 kOe is applied. *H*c of as-spun ribbon strongly depends on ?. The *H*c increases from 9 Oe at ?=0º to a maximum of 36 Oe at ?=80º. From the results, it can be concluded that as-spun ribbon has strong

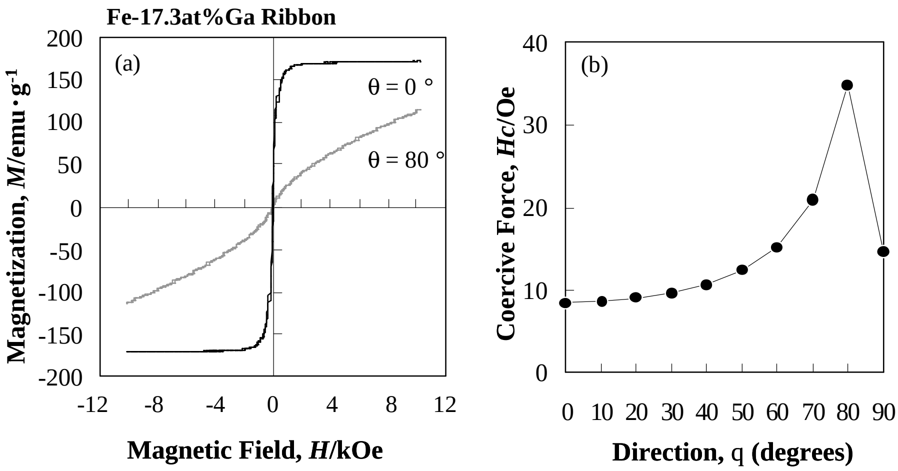

Fig.4 (a) Magnetization versus applied magnetic field loops and (b) dependence of coercive force on direction θ for as-spun Fe-17.3at%Ga ribbon. θ is rotation angle of sample (see in Fig.5).

magnetic anisotropy in ?=80º direction. This fact coincides with its strong [001]-oriented texture as shown in Fig.3(a). Next, we investigate dependency of magnetostriction on ? for as-spun Fe-17.3at%Ga ribbon, easy which has a easy axis of magnetization, [001], near ?=80º direction. Figure 5 shows (a) a schematic diagram of measurement method and (b) magnetostriction ? for ?=0º, 40º, 60º and 80º as a function of *H*. The ? was estimated by averaging values obtained by two gauges put on both faces of sample under loading stress a=10 MPa (not curvature). Longitudinal magnetostriction ? (TD at ?=0º) reaches easily a saturation value of 60 ppm in rather weak applied field of 1 kOe. Other ?'s for ?=40º, 60º and 80º increase continuously with *H*. Among these, a maximum strain was obtained for ?=80º, and ? for ?=80º reaches 200 ppm at *H*=10 kOe. It can be judged from these results that the large magnetostriction originates in the strong [001]-oriented texture near ?=80º.

In addition, note that ? of rapidly solidified ribbon is about 4 times as large as the bulk value.

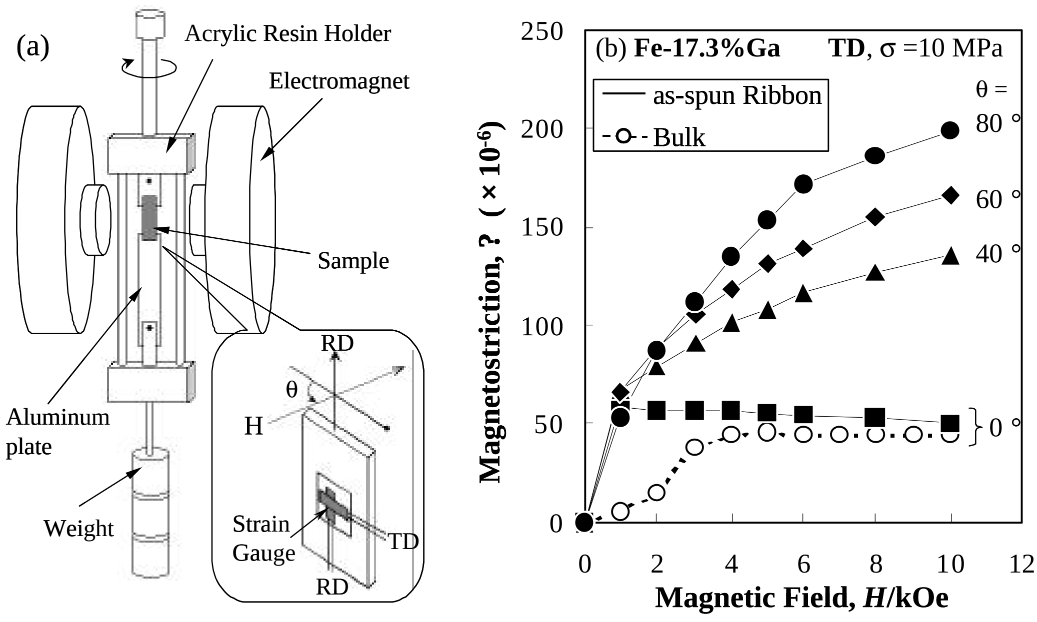

Fig. 5 (a) Schematic diagram of measurement method of magnetostriction by strain gauge and (b) dependency of magnetostriction on direction for as-spun Fe-17.3at%Ga ribbon and bulk.

Figure 6 shows dependency of the magnetostriction of Fe-15.1at%Ga ribbon on heat-treatments for (a) TD and (b) RD at ?= 80º. For 1173K•6h ribbon, ? of TD is approximately saturated to reach 60 ppm at *H*=8 kOe. On the other hand, for 1173K•0.5h and as-spun ribbons, ?'s of TD increases with *H*, reaching about 140 ppm and 90 ppm at *H*=10 kOe, respectively. In the case of RD, the ?'s for the three ribbons increase with *H* in similar fashion and there is no or small difference between them. From these results, it is found that ? of the ribbon increases with strengthening [001]-oriented texture and has little hysteresis

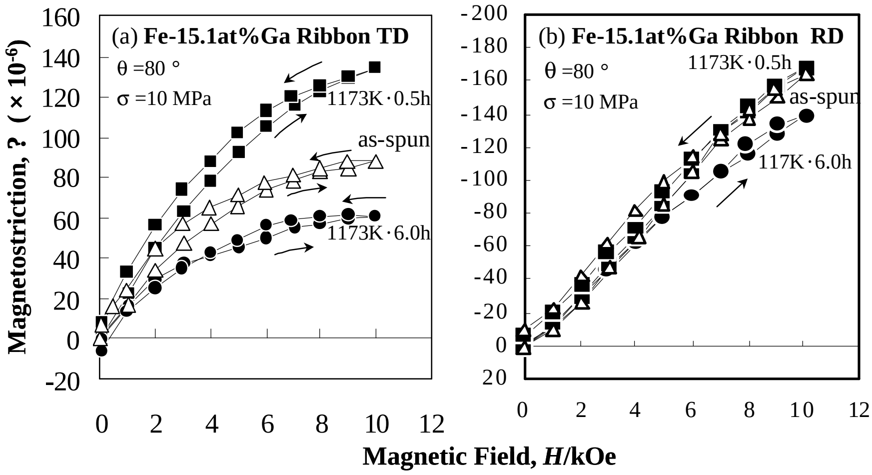

Fig.6 Magnetostriction of Fe-15.1at%Ga ribbons annealed for 0 h (as-spun), 0.5 h, 6.0 h at 1173 K.

3.3 Dependency of Magnetostriction on Ga Concentration

Figure 7 shows the *M-H* loops of as-spun Fe-13.7, -15.1 and -17.3at%Ga ribbons. We find that the saturation magnetization decreases with increasing Ga concentration. Magnetostriction ?'s of these ribbons for ?= 80º are shown in Fig.8: (a) is for TD and (b) for RD. The ?'s of TD for Fe-13.7 and -15.1at%Ga ribbons reach the saturation values of 60 and 100 ppm at *H*=9 kOe, respectively, while ? for Fe-17.3at%Ga ribbon increases steadily with *H* and reaches 220 ppm at *H*=10 kOe. On the other hand, in the case of RD, ?'s increases almost lineally with *H* for the three ribbons and ? of Fe-17.3at%Ga ribbon reaches -270 ppm at *H*=10 kOe. This value is 87 % of a single-crystal value, 311 ppm at room temperature [6]. When decreasing H, ? retraces its own step to where it started, i.e., there is little hysteresis. Moreover, it is seen that ? increases with Ga concentration, though the saturation magnetization decreases.

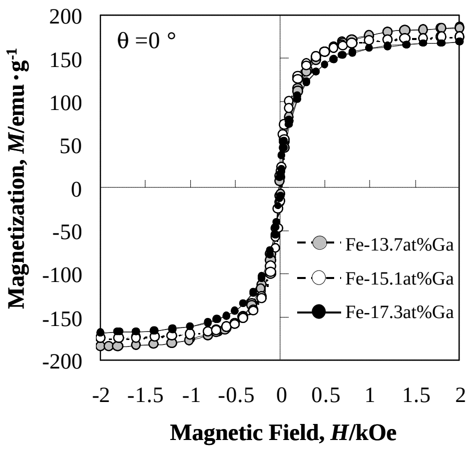

Fig. 7 Magnetization versus magnetic field loop for as-spun Fe-13.7at%Ga, Fe-15.1at%Ga, Fe-17.3at%Ga ribbons.

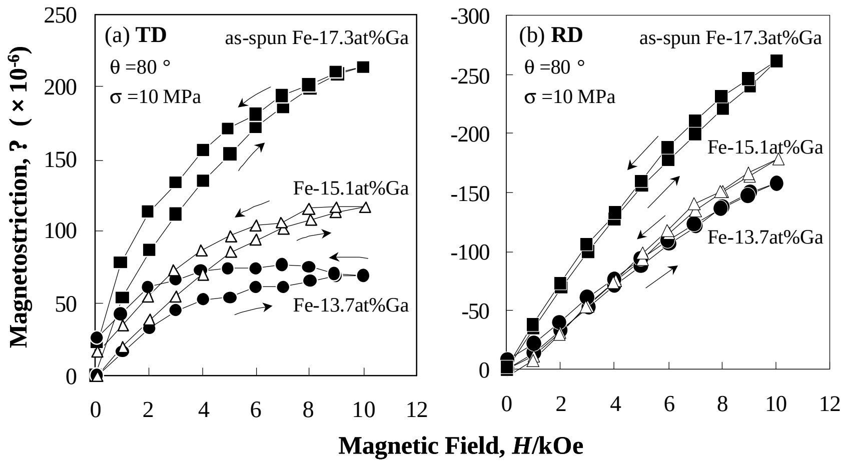

Fig.8 Magnetostriction for as-spun Fe-13.7at%Ga, Fe-15.1at%Ga and Fe-17.3at%Ga ribbons.

4. Conclusion

In this study, we examined a new polycrystalline Fe-Ga sensor/actuator alloy developed by a rapid-solidified melt-spinning method. Micro-structural texture and magnetostriction of $Fe_{1-x}Ga_x$ (x=0.137, 0.151, 0.173) rapid-solidified ribbons with bcc phase were investigated. The main conclusions are as follows:

(1) As-spun ribbon has the strong [001]-oriented texture possessing fine columnar grains, where the [001] axis tends to be oriented in the range of 0º to 40º from pole in the inverse pole figure and this tendency increases by short annealing.

(2) The large magnetostriction, 270 ppm, is obtained when magnetic field was applied in the direction parallel to the [001] axis of the texture and increases with Ga concentration, though the saturation magnetization decreases.

(3) Since the polycrystalline Fe-Ga ribbons prepared by rapid-solidification melt-spinning method has little hysteresis for magnetostriction and a good ductility, it is expected as a new magnetic-induced sensor/actuator material.

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